

1.3 Toward Future Computer Entertainment Systems

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I. THE BIRTH OF COMPUTERS

Sixty years have passed since the birth of ENIAC, utilizing over 18,800 vacuum tubes; 35 years have passed from the birth of the world's first microprocessor the "4004", integrating more than 2300 transistors. During these years, dramatic advances have been made in semiconductor process technology. Today, the most advanced microprocessor integrates several hundreds of millions of transistors on a single silicon chip, and boasts computing power a million times greater than that of the first microprocessor. Also, thanks to advances in semiconductor process technology, downsizing of chips has progressed, making it possible for PCs to excel in various applications, and significant improvements have been made in computing.

II. REAL-TIME COMPUTING

The main thrust of general-purpose computers is to process various and broad office applications, precisely and efficiently. Real-time responsiveness is generally not important. As well, software systems for general-purpose computers became more and more complicated, "comfortable" operation that was natural in analog and mechanical systems has been gradually lost. Even with a PC that incorporates the latest microprocessor and memory system, users are frustrated by the computer system stalling when accessing large files such as encountered in moving images, and even worse, the system itself sometimes freezes. One of the reasons for such performance degeneration is that both microprocessors and operating systems have made continuous efforts to downsize existing systems, while coping with the inherited architectures of traditional main-frame computers. Today, a wide range of applications can be realized by software solutions on general-purpose computers instead of by dedicated hardware; thus many hardware solutions are being taken over by computer systems. This is a rational progression, brought about by technology. Nevertheless, as a result of operation becoming more complicated, and real-time responsiveness largely disappearing, instinctive and intuitive behaviours expected by human beings become more and more absent. The user is compelled to read through hundreds of pages of manuals to uncover procedures and protocols, or to attend special computer schools. However, such knowledge, however obtained, soon becomes outdated. This is one of the causes for human hesitation in adopting computers.

On the other hand, when real-time responsiveness is emphasized, there are two elements that a human being can intuitively sense; One is the seamless continuity of motion that a human being cognitively feels to be real; and the other is the discernable predictability of the response time between action and reaction. Thus, currently, the frame rate required to allow consecutive still images to be perceived as a moving image is 24 frames per second, in the case of film, and 50 to 60 frames per second, in the case of NTSC/PAL TV systems. In the future, frame rate will be enhanced to become even higher for improving the fidelity of "expression". Researchers report that humans feel uncomfortable with delay in response. An experiment has been conducted in which participants viewed their surroundings via images provided from a camera worn on top of their heads, whose images were viewed through a Head-Mounted Display (HMD). The experimenters found that a very slight delay of (1/10 of a second) can make a human being feel discomfort similar to dizziness. As the delay becomes much longer, it becomes difficult for humans to even reach out to fixed objects. If this latency were to occur in driving a car at 55 miles per hour the car would travel 8 feet in 1/10 second, making it impossible to avoid dangerous objects. Thus, in mission-critical fields, secure real-time systems are mandatory, even today.

III. EMERGENCE OF COMPUTER ENTERTAINMENT SYSTEMS

One of the key applications of computers that have led the concept of real-time computing is in computer entertainment systems, which originally started as video game systems. Real-time responsiveness of computer entertainment systems must be quick enough to match the speed of the player, which means systems have to match human spinal-reflex actions, and intuitive actions through the human brain. In other words, the response time of the computer entertainment system must not disturb the player's action in any way, either directly or indirectly. Such a system is a sort of real-time simulation system for training reflex actions, accuracy, memory, and even thinking abilities of human beings.

Today, many users around the world are able to begin to make use of a computer entertainment systems as soon as they have the controller in their hand, without reading a single manual. This is because computer entertainment systems provide excellent user interfaces with real-time responsiveness. Users can receive direct reaction to their input, and can therefore learn how to manipulate the system within a short period of time. Hence, computer entertainment systems have always been a showcase for the most-advanced technology.

Once such computer entertainment systems are introduced to the market, the hardware is expected to be fixed for many years as a standard platform. This is because the development of a computer-game title requires a vast amount of time and effort, as well as continuous investment of business resources. In this business model, updating the platform in a short cycle would be a burden to both software-title developers and publishers, and also to end-users. Thus, there is an inclination to utilize the most advanced technologies on the future road map. System architecture must be simple, and tepid compromise should be minimized as much as possible. Having said that, it is important to note that once the system is introduced to the market, future flexibility and expandability are achieved by software.

In the last century, video-game systems effectively utilized mature technology to create electronic toys, primarily targeting children as their customers. The toy market, however, is not large enough to support development of the most-advanced technology. As a result, sound quality on early video-game systems was too basic, and graphics quality stayed at the level of simple paper-cutout characters. Fortunately, however, because children have fountains of curiosity, lack of expression was compensated for by their imagination. Meanwhile, rich stories were not possible because the systems had to utilize a small data capacity of mask-ROMs; Consequently, video-game systems were not attractive enough for creators and designers; and, for most adults, computer games were placed outside the realm of their interest.

But, a new development started to create innovative game content that had never existed before, by pulling away from the old way of thinking, and aggressively taking in the most advanced technology. In short, what was necessary for progress was to establish a vast campus to attract creators and artists of the world. Fortunately, in the long history of humanity, computer science is, relatively speaking, a new technology, still in its infancy. As well, the semiconductor technology that underpins computer science was also making steady and continuous progress in micro-fabrication, to the point of surpassing the wavelength of light. If this totally new technology, that human beings had never possessed before, the computer, could be set free from offices, and be made a medium for creativity and communication, it would have the potential to grow to be the next generation of entertainment – equivalent in significance to recorded music, movies, and TV. The movement to create the world of "computer entertainment", the fusion of computer and entertainment, started in 1994 with the "Playstation". (See Fig. 1.3.1)

IV. SOUND SYNTHESIZER

In the world of sound, where the fusion of computer and entertainment had started earlier, it was already possible to process and generate various sounds in real-time with the emergence of DSP. One typical application of this technology can be found in the creation of electronic musical instruments that must support the processing of the keyboard touch of a pianist communicating full rich emotions and feelings along with extreme techniques. Already in 1980, some avant-garde performers were in possession of the first digital sampling sound sources, devices that cost several hundreds of thousands of dollars per system. They were innovative devices that created sounds in real-time by taking in fundamental tones through digital sampling and synthesizing by note and by velocity. Through these devices, the breadth of musical expression was expanded. Today, the functions that these devices supported can be performed by software running on a PC, but in the early 1980s, this was still much-coveted technology.

The first thing we imagine when thinking back to computer music in 1980 is the “pip-pip” sound. Although it was well accepted as the sound of the computer, it was not truly pleasing - a more diverse and mild sound source was gradually sought. Accordingly, the “FM sound” was invented and adopted first by electronic keyboards, and then by coin-operated game systems, PCs and other mainstream applications. While the FM sound allowed generation of soft sounds, and used a smaller amount of data than in the past, it was far from “natural” sounds, those experienced in real-life, such as heard in the rich musical expression of a full-sized orchestra. Nevertheless, as a result of significant improvements in both the processing power of DSP and the capacity of solid-state memory in the late 1980s, digital sampling systems implementing sound sources began to be used widely in electronic musical instruments. In 1990, the first game console supporting PCM sound with digital sampling capability was born. At that time, the cost of a digital-sampling sound source was 1/1000 of what it had been in 1980. And, by adding ASIC functionalities to DSP, it became possible to support the majority of sound sources, including the conventional FM sound in addition to that of traditional instruments and the human voice, in real-time, giving rise to the birth of the “Sound Synthesizer”.

V. GRAPHICS SYNTHESIZER

Efforts to utilize computer technology in art, design, and entertainment, have come to fruition in several areas. One remarkable example is computer graphics. In the 1980s, this extremely important computer technology had diverged into two different streams: One stream strove to generate very precise graphics, regardless of the time required during the process; while the other stream put more emphasis on real-time responsiveness, but tolerated some roughness in graphics expression. The former developed in motion-picture production, while the latter developed in computer entertainment.

Because computer entertainment systems use home televisions as their graphics-display device, the entire graphics-processing cycle must be done in real-time, concurrently with the TV refresh rate. As it was difficult for general-purpose computers to generate all graphics matching TV-signal quality in the 1980s, real-time responsiveness was secured by reducing the number of colors and lowering the resolution using hard-wired logic. An example of the pseudo-2-D computer graphics that typified rendering in the 1980s is the combination of a scrollable background (BG) with multiple objects (Sprites) that are moveable in pixel units. This technique was invented and introduced first in coin-operated game systems. Because they were able to realize smooth graphics motion at lower cost, BG and Sprite systems won the battle with the competition - home game systems, based on PC technology, that were released around the same time. The prevailing perception at that time was that computer game consoles

were nothing more than a toy, and that simple employment of PC technology should suffice. In fact, various kinds of home game systems were introduced to the market in the early 1980s, and although they attracted much attention, many game systems gradually disappeared.

One of the key technical performance criteria for game graphics is real-time responsiveness. While home game systems, based on the PC technology of that time, used character-generator-based scrolling. Correspondingly, they were limited to a scroll resolution of 8 pixels, while dedicated game consoles were able to express smooth motion images with scroll resolution of a single pixel. At the same time, dedicated game consoles were able to execute the entire graphics-processing cycle in synch with the graphics refresh rate of a TV, whereas PC-based home game systems renewed graphics images out of synch, whenever processing was completed. Consequently, PC graphics flickered when quick moves were made, and comfortable and smooth manipulation of the controller was impaired. Meanwhile, the 2-D Computer Graphics (CG) that dedicated game consoles created became the standard for computer games in the 1980s and the 1990s, and many masterpiece game titles were born.

Nevertheless, while 2-D CG had some stylistic warmth, it was difficult to express the concept of space, a natural concept in real-life. In the 1980s, to freely fly around in 3-D space was still nothing but a dream. In fact, no commercial system capable of drawing 3-D CG in real-time was realized until 1989. On the other hand, in the area of movie production, where real-time responsiveness was not required, adoption of CGI Computer-Generated Imagery (CGI) production started to become popular in the 1980s. In 1982, the first CGI movie that combined wire-frame and live-action images was released, spearheading advances in the field of CGI, which has now blossomed into a mainstream technology. In 1990, the release of a graphics workstation capable of drawing high-resolution 3-D CG in real-time stole the limelight. While it could draw a hundred thousand polygons per second, latency in graphics rendering posed a significant obstacle for its application in areas that require high-speed response, especially for utilization in computer games. This latency was caused by the use of a multiple-pipeline architecture that aligns multiple processors in series for the purpose of executing huge amounts of calculation. Because processing was sent from one pipeline stage to another concurrently with the graphics refresh cycle of a display device, it took 1/10 second to go through the entire pipeline process. In computer games, latency between input and image output is crucial and it must be held down to between 1 and 2 fields (32 to 40 milliseconds) at the most, which is twice the TV refresh time.

To solve the long-latency problem, a new architecture was developed and adopted in a computer entertainment system in 1994. This new architecture placed multiple processors in a parallel configuration on a single silicon chip, enabling the execution of multiple tasks as one program. Each 3-D polygon was overlaid with texture mapping to create a system that had cost several hundreds of thousands of dollars in the previous decade. Correspondingly, this produced a home system of 1/1000 the price, motivating many game titles to move quickly from the world of 2-D CG to 3-D CG. This new architecture also made it possible to map motion images onto a polygon as texture, instantly and greatly expanding the range of graphical expression. Because this system was able to express texture-mapped rectangular polygons that stand simultaneously in a screen as 2-D sprites, it became possible to fuse a video image with 2-D and 3-D CG images in a single architecture.

In 1999, large-scale DRAM embedded in logic allowed the connection of graphics processor and memory with an ultra-wide bus

width of several thousands of bits. Accordingly, VRAM bandwidth, which had been a bottleneck in rendering on traditional graphics systems, was improved by more than two orders of magnitude. Traditionally, DRAM embedded in logic had been either of small capacity, or was not easily, some early solutions, simply combined multiple chips to reduce the number of components and shorten connections. Thus, this new approach to gaining huge bandwidth by taking advantage of the characteristics of truly-embedded DRAM became a mainstream feature in subsequent ultra-high-speed memory systems. This large-scale LSI was incorporated as the "Graphics Synthesizer" in the next generation computer entertainment system launched the following year, (see Fig. 1.3.2).

VI. EMOTION ENGINE

Although the introduction of the "Sound Synthesizer" and the "Graphics Synthesizer" made it possible to generate sound and graphics in real-time, enormous amounts of work was still needed to create life-like scenes and generate rich animation. This was a waste, both of huge amounts of time and of business resources. As well, it blunted the intuitive creativity of artists and designers: Many image frames had to be produced in advance in non-real-time, because the calculations to produce them from key frame data (the usual basis of animation), and from skeletal physical modeling, required huge amounts of computer processing. However, the result was still unsatisfactory: No matter how sophisticated the graphics and sound became, the overall motion was still unrealistic. The fact is that for general-purpose computer systems of a decade ago, it was extremely difficult to execute such huge amounts of computing in real-time. Bandwidth to transmit data was also a bottleneck.

In 1999, the "Emotion Engine" was developed to help solve these problems for computer entertainment applications. The details were reported at ISSCC1999 [1-2] and at HOTCHIPS1999 [3]. It was the world's first 128-bit microprocessor with two sets of co-processors based on floating-point functionality for graphics and animation. The "Emotion Engine" was first implemented as a 240mm² silicon chip, integrating 10.5 million transistors and fabricated using a 0.25- micron 4-layer-metal process. At this point, the performance of this microprocessor, developed for computer entertainment systems, exceeded that of all general-purpose processors in both floating-point calculation performance and bus bandwidth.

The "Emotion Engine" accelerated the trend from Media Transformation toward Media Synthesis. (See Fig. 1.3.2) In computer entertainment applications, whether for generating characters' behaviors and facial expressions or for giving movement to body and limbs (through inverse-kinematics techniques combined with skeletal physical modeling), or for subtly expressing waving lotus and tremulous leaves, a new breath of life was given to the computer-generated 3D world.

VII. REALITY SYNTHESIZER

In computer entertainment today, there is an increasing inclination to create more realistic expression. This stems, in part, from the fact that display systems in the living room are quickly shifting from CRT to larger-screen flat displays with a large aspect ratio, 16:9. Correspondingly, progress to seek reality on large-screen displays is being made in the following two ways:

One essential element has been the development of high-quality graphics-rendering technology. Traditionally, 3-D CG combined large numbers of polygons with texture mapping and expressed-light- source-based shadowing and reflection. Nonetheless, real-time expression of complex scenes, soft light reflections, depth queuing, and multi-layered translucency, were a challenge. It is now apparent that pixel-based rendering, rather than polygon

rendering, is the right solution in a more realistic world. Furthermore, pixel-based rendering procedures should be flexible enough to meet a wide variety of rendering conditions. Thus, a number of programmable shaders are now being developed. Through this pixel-based technology, graphics on computer entertainment systems has reached the same level of quality as that of the latest movies.

There is second essential element in the pursuit of reality. Images must not only be beautiful as still pictures, but each object and character must behave naturally when in motion. Natural motion requires vast amounts of physics simulation, but without it, overall graphics would not be much different than that of existing computer entertainment systems. Calculation for natural-motion graphics is mainly in floating point, and to handle various application, flexible programming by application software becomes necessary.

In 2004, "Cell," a broadband processor, was developed. It employs the most advanced multi-core architecture, comprising multiple independent processors and each coupled via an ultra-high-speed bus capable of executing enormous amounts of calculation when connected in a parallel configuration. The total number of transistors in one "Cell" processor is 234 million. By utilizing a 90nm SOI process, they are all integrated on a single 221mm² silicon chip, as reported in [4 to 7] at ISSCC2005. Consequently, single-precision floating-point calculation performance equivalent to a super computer of over 200GFLOPS has been realized. As each parallel floating-point calculation unit can autonomously execute objects comprising programs and data, parallel processing in harmony with other "Cell" systems in the home and available over the network, is also possible. Correspondingly, in the future, because "Cell" will be connected to the broadband network, powerful security and independent memory-protection features will become imperative.

VIII. NETWORK COMPUTING

For real-time network computing, it becomes necessary to upgrade narrowband servers and switches, which are now bottlenecks on the network, to establish truly ultra-high broadband network systems. However, it would take a considerable time to upgrade, the present system. Rather, an alternative is available. Consider the possibility that most- efficient way to realize effective network computing on a narrowband network, is to form a huge "Cell"-based super-computer-like server as an application server to which many client systems have access. If network client systems incorporate "Cell" processors, real-time responsiveness is by and large secured by exchanging only a small number of objects, and users will be able to feel as though they have their own super-computer. Users could freely access a huge cyberspace, and also become part of it. In this cyber-space, various interactions become possible in real-time, inspiring not only future forms of entertainment but also various new industries.

More locally, an ideal broadband network environment is easier to build in the homes. Laser technology and ultra-high-speed wireless-communications technology will dramatically change the network environment in homes. Our homes are already filled with various entertainment contents, including, for example, a library of photographs, movies of children growing up, TV programs, favorite music, and games from the old days. The time when they are digitized, processed, and stored on home servers, for the family to comfortably access wherever they are in the mood is just around the corner!

IX. WIRELESS NETWORK CLIENT

It is natural for people to enjoy their favorite entertainment contents whenever and wherever they are; in their homes and even when traveling, by casually accessing their home servers through

their mobile clients. In 2004, the "Location-Free" concept was introduced. This enables users to access their home-base terminal through the Internet, and enjoy local content - local TV programs and content stored on HDD recorders even from abroad. By expanding this concept, it will also become possible to access computer entertainment system in the home, from mobile clients in real-time. Thus, mobile clients instantly become the remote display and interface for home-computer entertainment systems.

In 2004, a handheld computer entertainment system was introduced, that included various media players and wireless-network connectivity. (See Fig. 1.3.3) This system is equipped with a high-resolution screen with an aspect ratio of 16:9, the same as flat displays used in the home. Many functionalities, such as a real-time 3-D CG engine, the most advanced H264@MP-level3 video decoder, a Virtual Mobile Engine to support various codecs, a dual 32-bit RISC processor, a total of 4MB of embedded DRAM, USB and various other I/O, were all integrated on a single silicon chip. The system employs various other innovations, such as utilization of reconfigurable logic, dynamic activation, gated-clock control of function blocks, and adoption of variable system clock, all to lower power consumption as much as possible while maintaining a high level of functionality and performance. The total transistor count is 89 million. By utilizing 90nm embedded DRAM logic, they are all integrated in an 86mm² 540pin LFPGA[8].

X. COMPUTER VISION

In the future, when broadband servers in offices and homes are connected through high-speed optical communication networks, and advanced mobile clients are linked through the wireless network, there is little doubt that large numbers of networked sensors will form a "sensor network." Then, it will become possible to have Internet access to various selected sensors from office and home. Even today, many network-based imaging systems are delivering images via the Internet. However, graphics quality as seen, immediately in resolution and frame rate, is still disappointing. Security cameras installed in airports, banks, and stores, are low-resolution, low-frame-rate and have narrow dynamic range, and the quality of video images provided through such recording systems is unsuited for computer processing. Dramatic improvement is expected in the near future through the development of imaging devices and graphics processors. Limitless numbers of such improved sensors will then be connected to the Internet, and we will see the dawn of the "Sensor-Network" era, with each sensor possessing a unique IP address.

In the world of computer entertainment systems, sensors will become the key human interface in the future. Multi-access sensors and video cameras are already used as input sensors. In 2003, a game system that interactively manipulated objects on-screen by capturing the player's body actions in real-time, was introduced. Because it must detect position and movement of objects as video, frame rate should be as high as possible. And, processing power of the associated digital image-processing systems should match this high frame rate. Such a balanced system would realize the "Vision System" that captures positions and movements of objects, to be coupled to with physical simulation processes. By such techniques, it will become possible to link computer entertainment applications with the live world, all in real time.

A variety of sensors for detecting and measuring vibration, acceleration, distance, weight, temperature, and pressure, can be combined to form a "sensor network." Even moving animals, invisible at night, can be detected. Clearly, such a "sensor network" can be applied in security systems for homes and communities. And, if incorporated in cars, obstacles and road signs can be instantly recognized. As well, future robots will by-and-large incorporate a high-level computer-vision system.

XI. SEMICONDUCTORS AND COMPUTER ENTERTAINMENT SYSTEMS

Today, the computer entertainment industry is driving semiconductor demand with tens of millions of computer entertainment systems shipped annually. Computer entertainment systems target the most-advanced technology to be available on the future road map, typically three calendar years ahead or one process generation ahead. Correspondingly, a system must start off by using large-size chipsets at launch. But during its life cycle, the system goes through two generations of semiconductor fabrication processes to enable downsizing. Also, progressive integration of chips is used to reduce manufacturing costs, and to further enable mass production. (See Fig. 1.3.4)

The die size of processors used in computer entertainment systems during the past 12 years has become dramatically smaller. The size of each chip at product launch is generally larger than that of processors used in general-purpose PCs. (See Figs. 1.3.5 to Figs. 1.3.10). However, because mass production can be expected to continue over the long-term, continuous integration efforts, including the improvement in yield rate, are easy to carry out. Recently, the most technologically advanced DRAMs, communications LSIs, semiconductor lasers and various sensors, are being deployed in computer entertainment systems. The development of semiconductors and computer entertainment systems is inextricably linked. (See Fig. 1.3.11)

Real-time computing will bring a new paradigm shift for both the computer and semiconductor industries. Computer entertainment systems and applications are now leading this trend.

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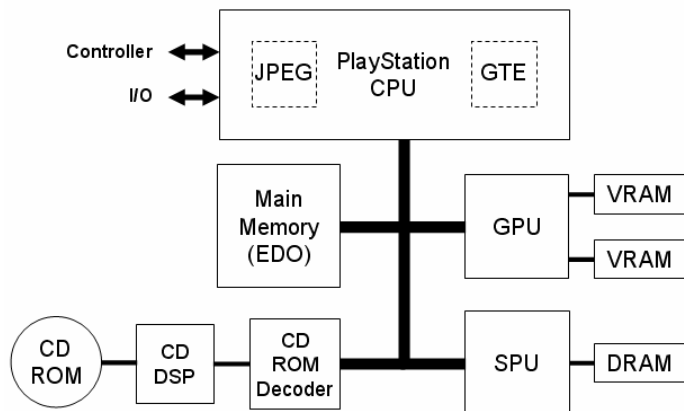


Figure 1.3.1: Playstation (1994): block diagram.

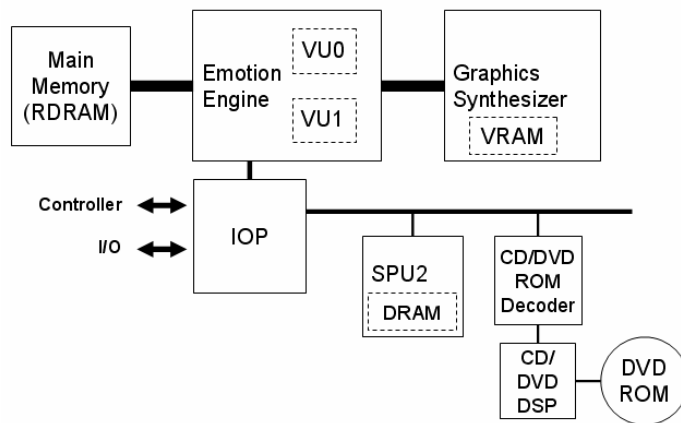


Figure 1.3.2: Graphics synthesizer and emotion engine (2000) emphasizing embedded DRAM

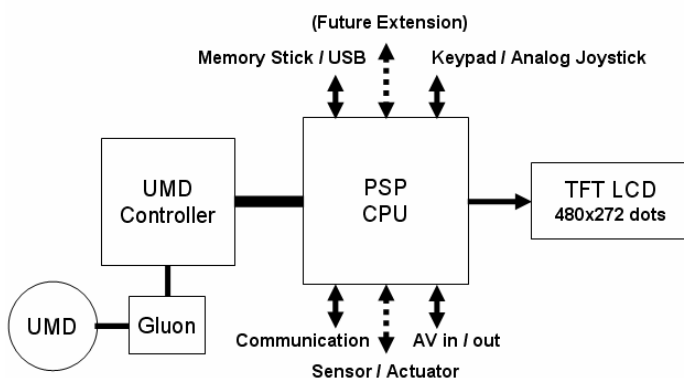


Figure 1.3.3: Handheld computer-entertainment system 2004.

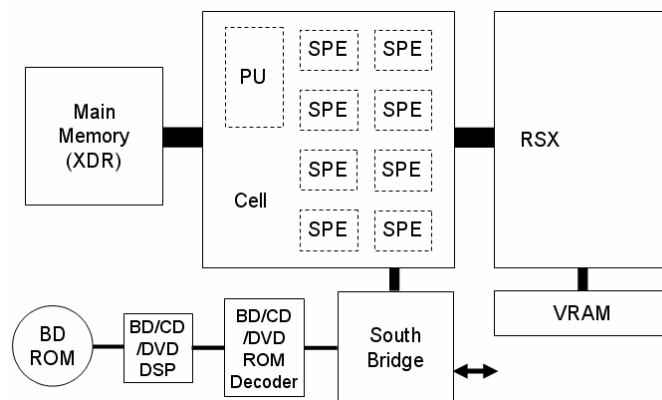
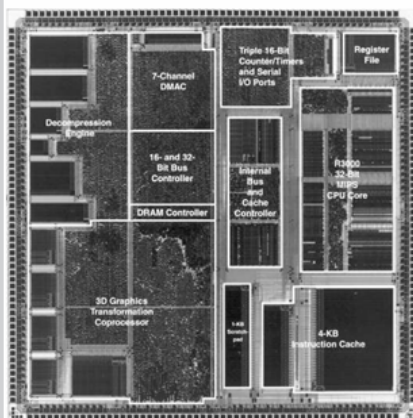
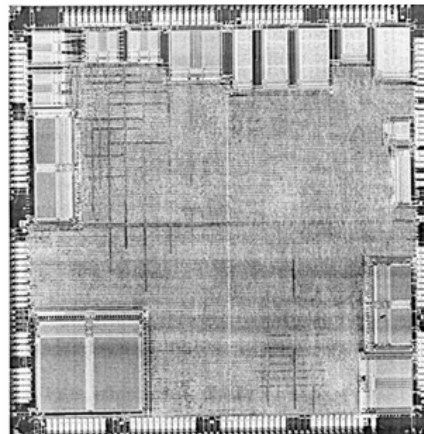


Figure 1.3.4: Structure allowing progressive integration.



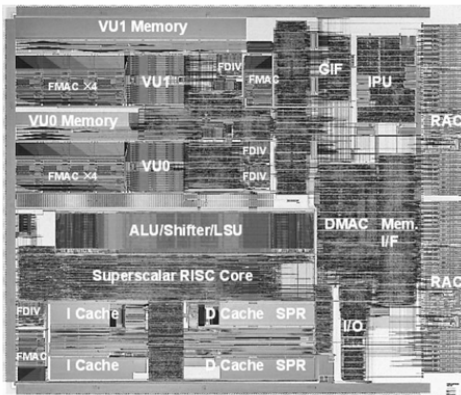
32 bit CPU
33.8 MHz @3.3V
1.0 million Tr.
128 mm²
0.6 um
3 Metal Layers

Figure 1.3.5: Continuing integration I.



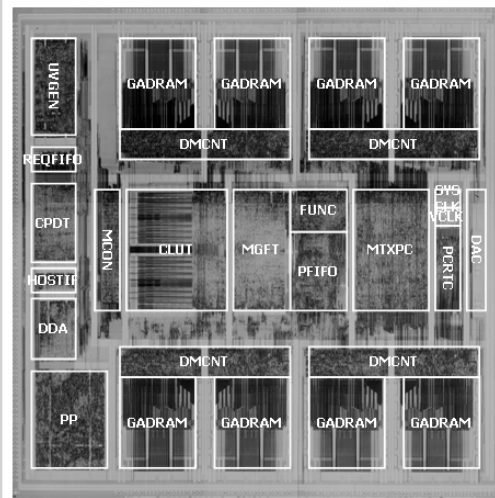
32 bit CPU
33.8 MHz @3.3V
850 K Tr.
46 mm²
0.35 um
2 Metal Layers

Figure 1.3.6: Continuing integration II.



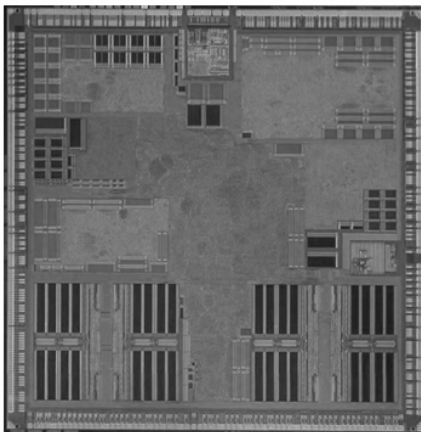
128 bit CPU
294 MHz @1.8V
10.5 million Tr.
17.0 mm x 14.1 mm
(240 mm²)
0.18 um (gate)
0.25 um (metal)
4 Metal Layers
540-pin PBGA
13 Watts

Figure 1.3.7: Continuing integration III.



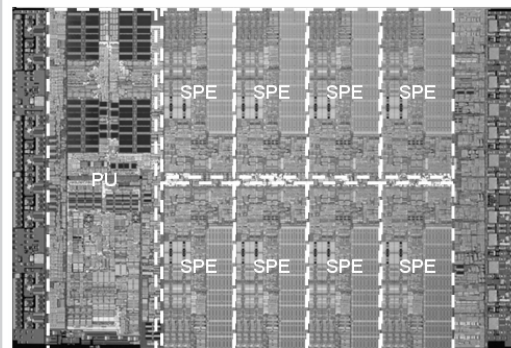
Graphics Engine
147 MHz @1.8V
4 Mbyte eDRAM
(2,560 bit bus)
48 GB/sec
43 million Tr.
279 mm²
0.25 um eDRAM
4 Metal Layers
384-pin PBGA
10 Watts

Figure 1.3.8: Continuing integration IV.



333 MHz
@0.8V-1.2V (core)
4 Mbyte eDRAM
89 million Tr.
86 mm²
90 nm eDRAM
7 Metal Layers
540-pin LFPGA
< 500 mW

Figure 1.3.9: Continuing integration V.



Multi-core
1 x PU
8 x SPE
3.2 GHz @1.0 V
234 million Tr.
221 mm²
90 nm SOI
8 Metal Layers

Figure 1.3.10: Continuing integration VI.

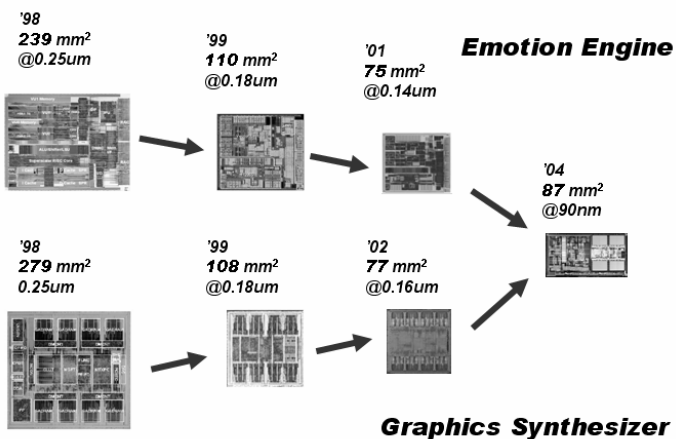


Figure 1.3.11: Convergence linkages (1998 to 2004).

